(Almost) Completion of Cryomodule-1 Tests

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on behalf of the CM-1 team
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U.S. DEPARTMENT OF ENERGY

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Introduction / What is CM1?

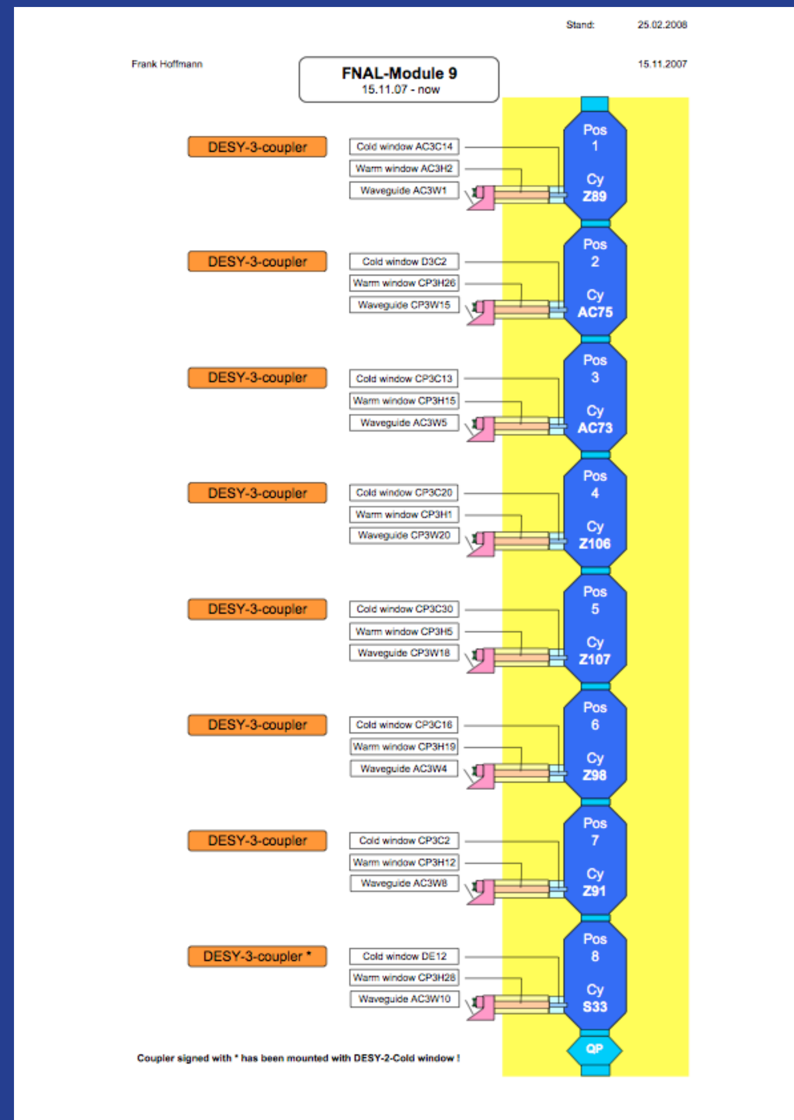
- Cryomodule 1, also dubbed 'S-1 Local'
- TTF Type III+ 8-cavity cryomodule
  - First one in the U.S.
- Provided to Fermilab by DESY as a 'kit'
  - Assembly by Fermilab, DESY, INFN-Milano
  - In exchange for 3.9 GHz cryomodule
    - Now in routine operation at DESY/FLASH
- Assembly at Fermilab
- Now installed at the refurbished New Muon Lab experimental hall and a chief component of the Advanced Superconducting Test Accelerator (ASTA)

Achievements/Events since previous AEM Update (June 2011)

- Cold Conditioning and initial performance checks completed individually on each cavity
- Waveguide distribution assembly installed
- Entire module powered (first time on 6 July)
- LLRF calibration; detailed single cavity evaluation
- Lorentz Force Detuning Compensation/Adaptive Algorithm
- Low Level RF studies with DESY colleague
- Long Pulse Testing
- Klystron Modulator repair
- Thermal Cycle/Repair of IN_2 leak
- ‘Routine’ Operation

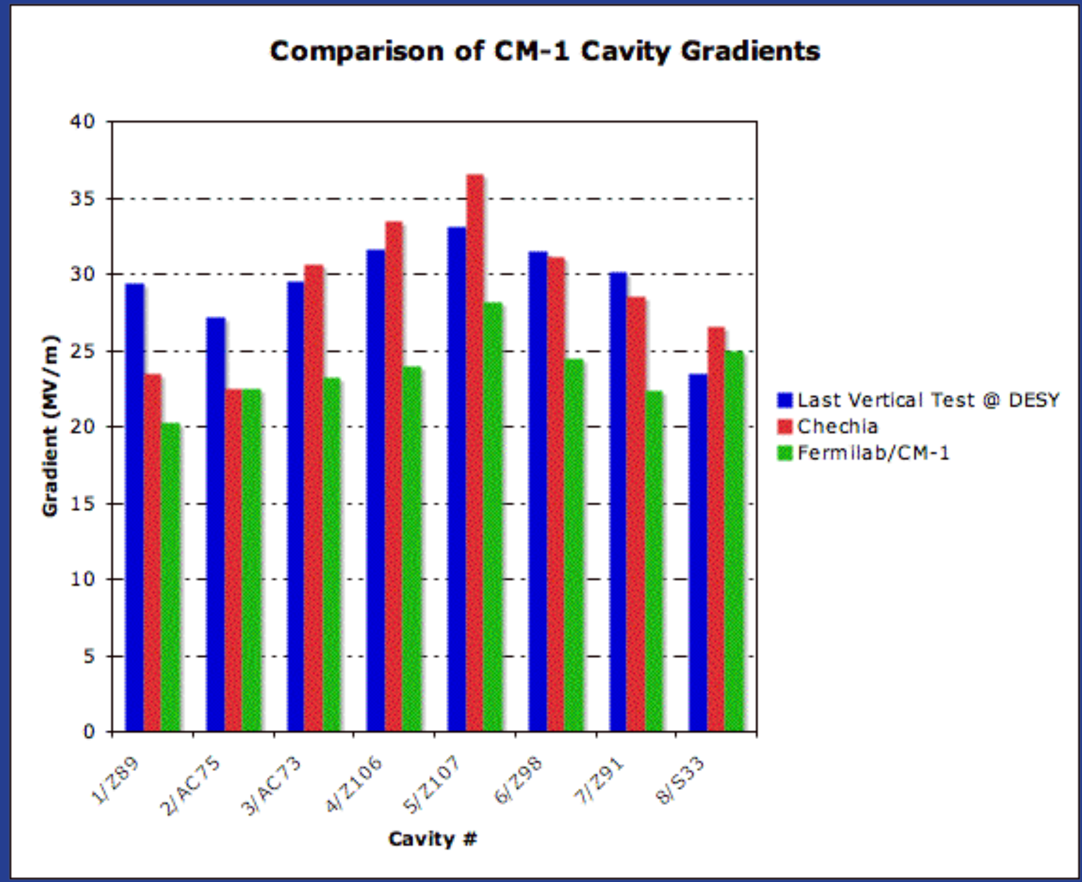
Cavity Performance Summary

Cavity	Peak E_{acc} (MV/m)	Estimated maximum Q_0 (E09)	Limitation/Comments
1/Z89	20.2	11	'soft' quench/heat load
2/AC75	22.5	12	Quench
3/AC73	23.2	0.43	'soft' quench/heat load
4/Z106	24*	2.3	*RF-limited
5/Z107	28.2	39	Quench
6/Z98	24.5	5.1	Quench
7/Z91	22.3	4.7	'soft' quench/heat load
8/S33	25	18	Resonant frequency at 1300.240 MHz; tuner motor malfunction



Cryomodule Performance - Peak Gradient

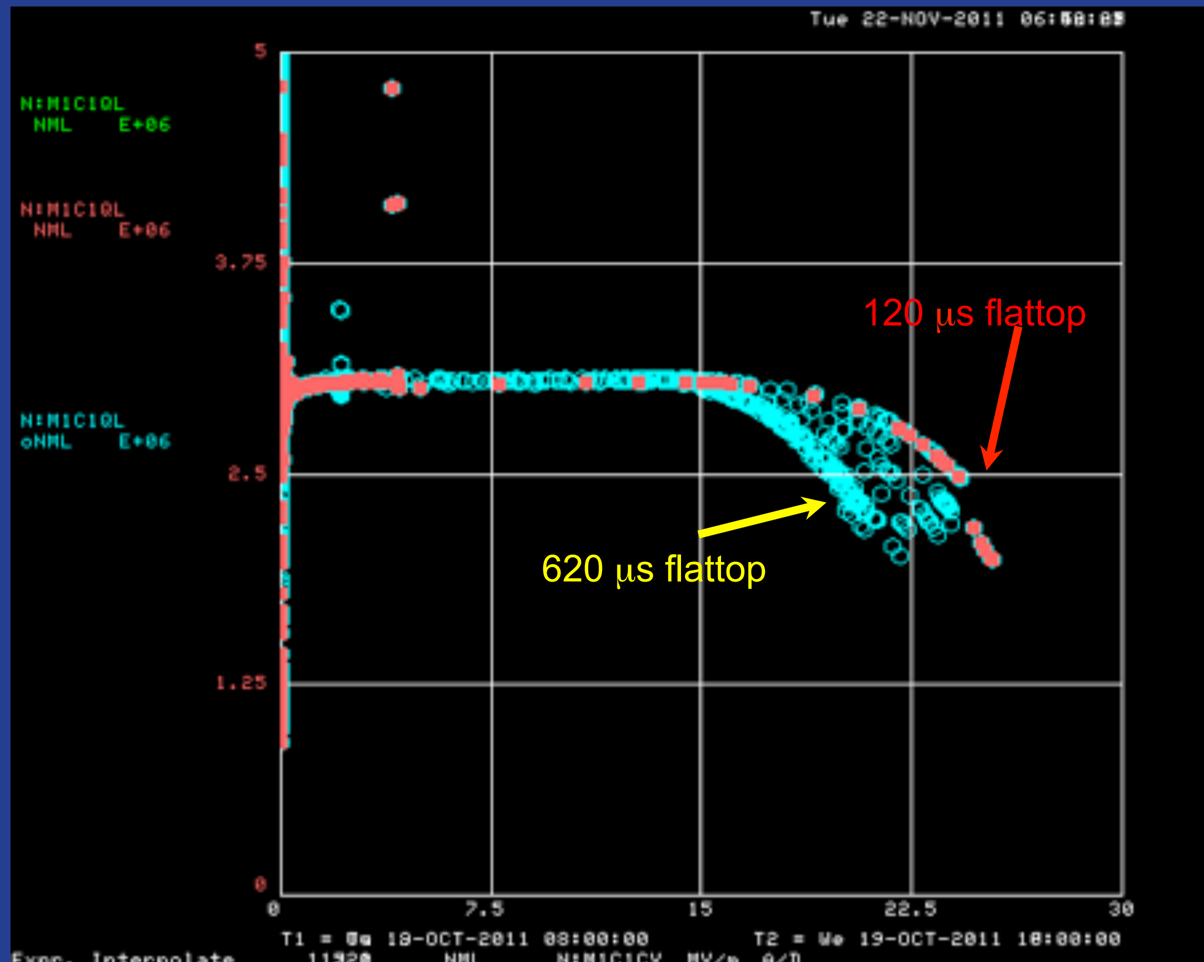
- Determine final signal calibrations
- Cavity Peak Gradients
  - All cavities on resonance
  - One cavity on resonance at a time
- ILC-like operating conditions



	1	2	3	4	5	6	7	8	Mean
CM-1 Peak Gradient	20.2	22.5	23.2	24*	28.2	24.5	22.3	25	23.7
Ratio compared to Chechia	0.860	1.00	0.758	0.716	0.773	0.788	0.782	0.940	0.827

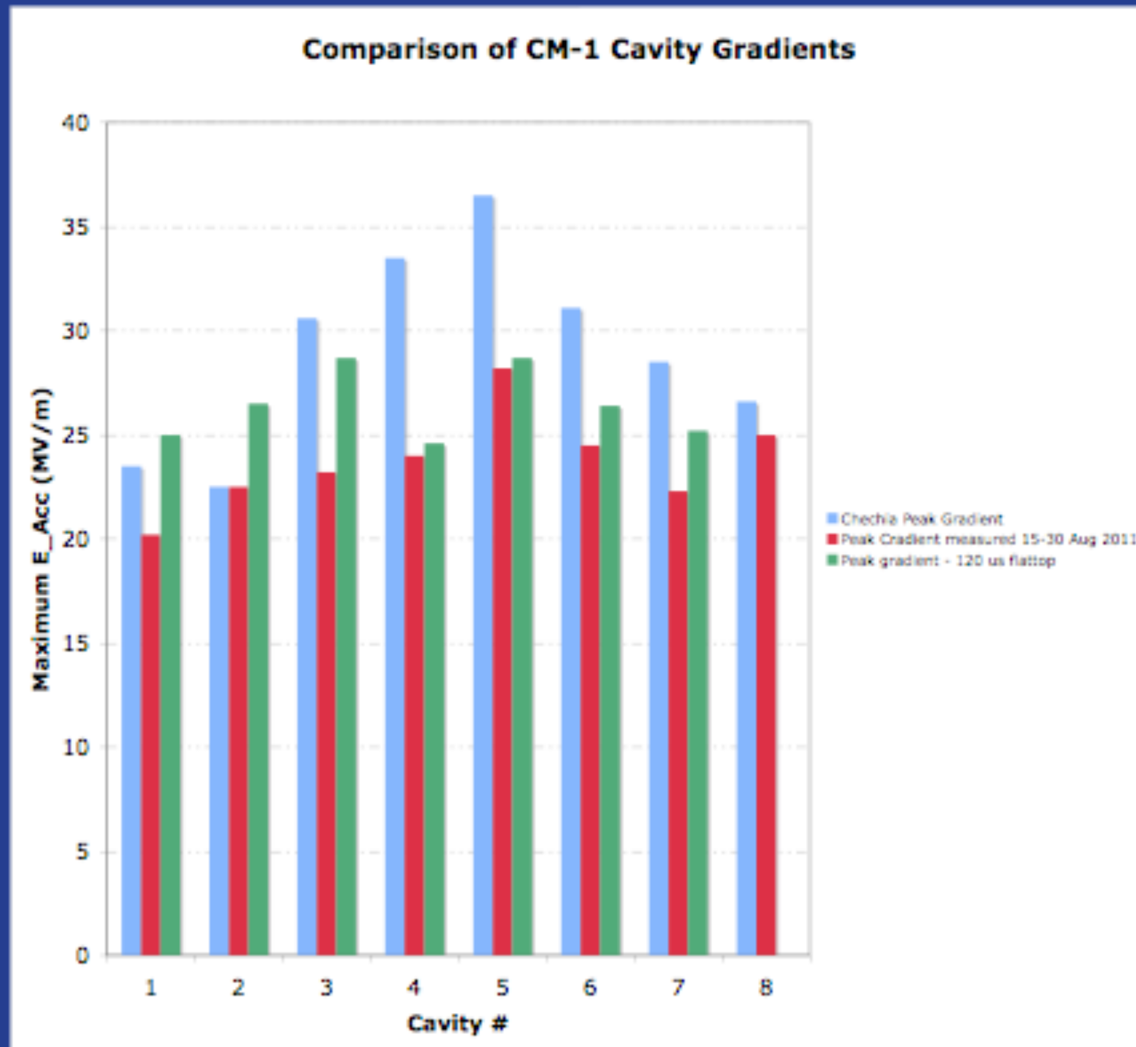
Vary Flattop Length

- Cavity #1
  - Variation of Q_L and peak gradient with flattop length
  - 100 μs increments in flattop length
  - Onset of Q_L drop from 14 - 17 MV/m
  - Peak gradient increased from 21 to 25 MV/m



Vary Flattop Length

- Peak gradients all increased (green compared to red)
- No clear indication of increased HOM heating on suspect cavities
- Quench limit generally inversely proportional to flattop length
- Some cavities limited by available RF power



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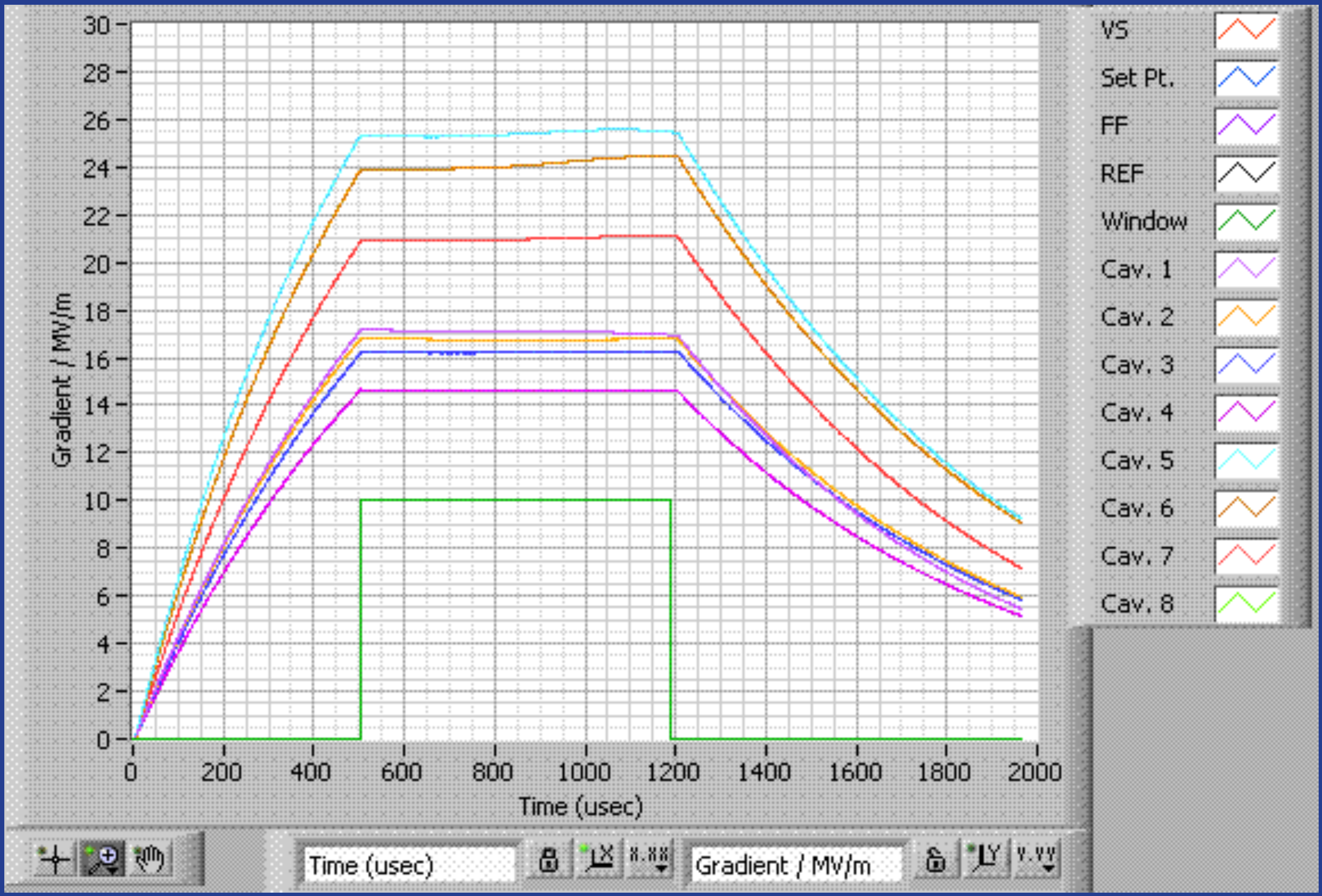
Cavity Performance Summary

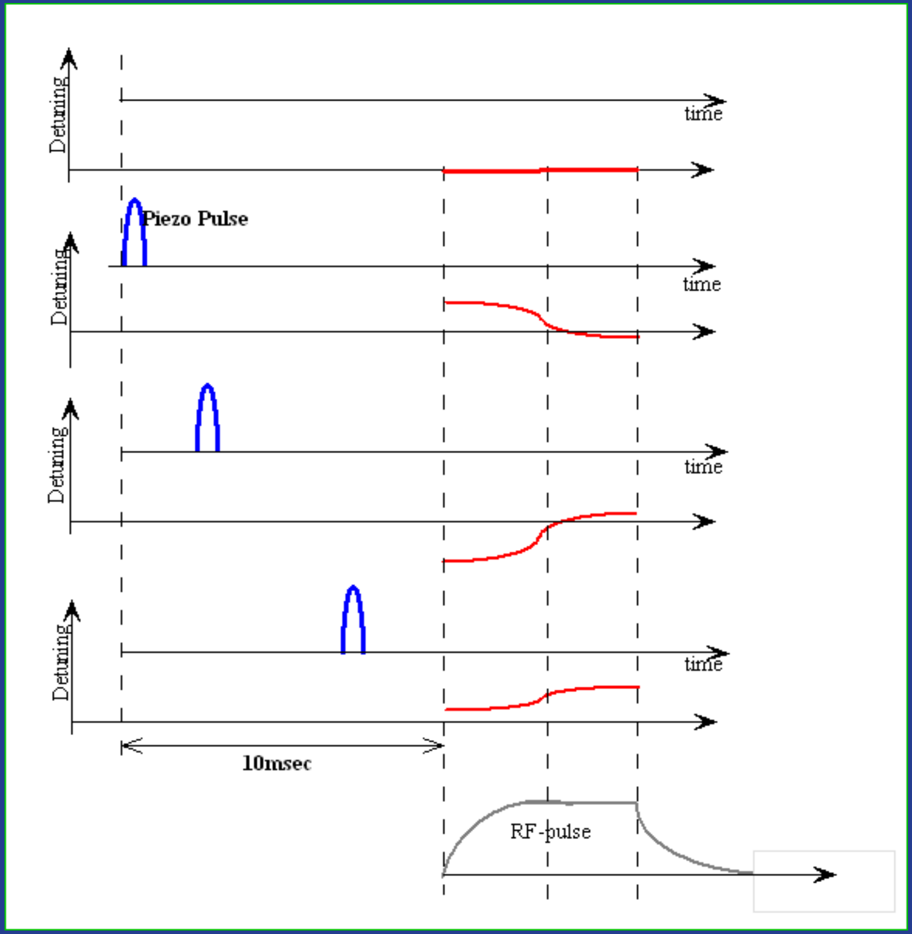
- Cryomodule evaluation focusing on
  - Final calibration values
  - Re-check individual cavity peak performance and limitation
- Lorentz Force Detuning Comp.
- Low Level RF
- Routine operation at 5 Hz.



Adaptive Least Square LFD Algorithm

The response of the cavity frequency to the piezo impulse (TF) can be easily measured when cavity operated in CW-mode.

Since it is often not convenient to connect a pulsed cavity to CW source we developed alternative technique to measure this response (TF) when cavity operated in RF-pulse mode.



Piezo/cavity excited be sequence of small (several volts) narrow (1-2ms) pulses at various delay.

The forward, probe and reflected RF waveform recorded at each delay and used to calculate detuning.

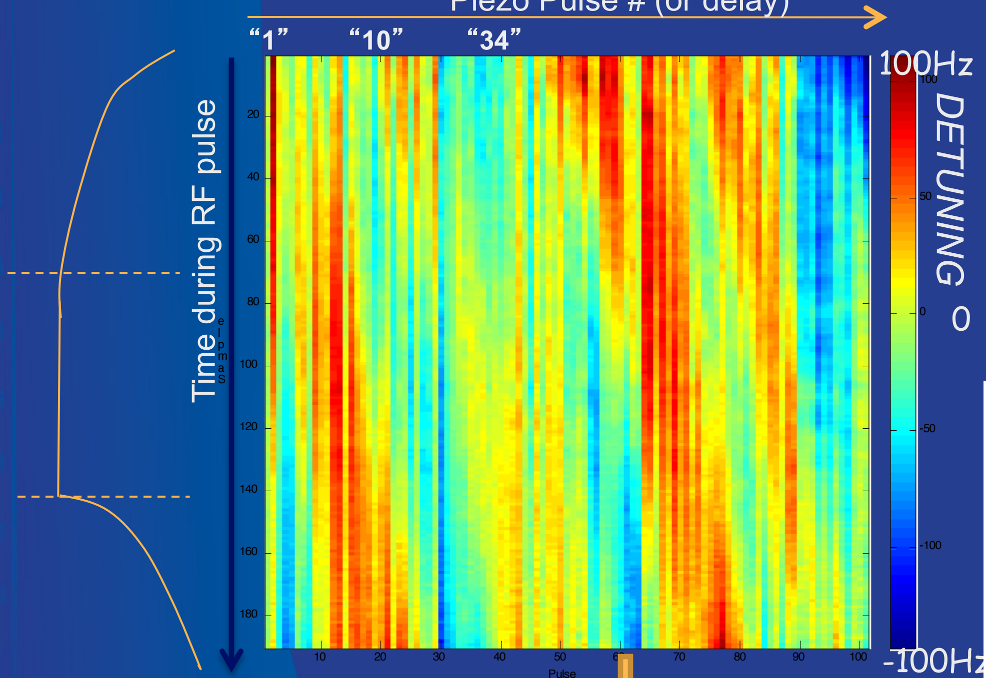
[Response Matrix]

Details of Adaptive LS LFD Algorithm at :

"W. Schappert, Y.Pischalnikov, "Adaptive Lorentz Force Detuning Compensation". Fermilab Preprint – TM-2476-TD. And at PAC2011.

Adaptive LS LFD Algorithm

Response Matrix



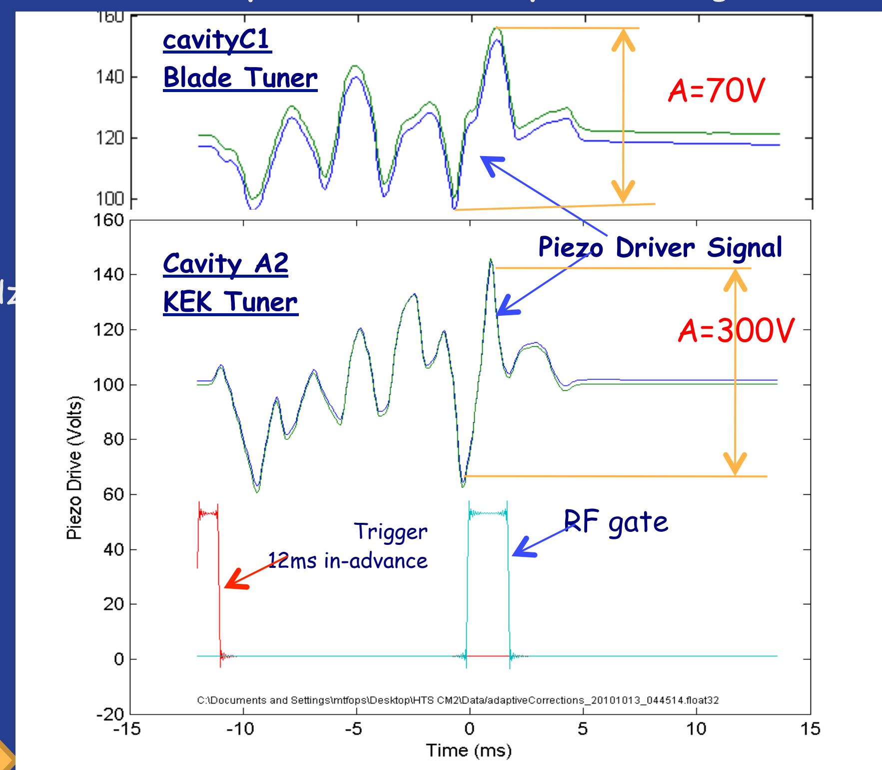
As operating conditions vary, the RF waveforms can be used to measure any residual detuning. The response matrix can then be used to calculate the incremental waveform required to cancel that residual detuning.

Invert the response matrix and determine combination of pulses needed to cancel out the LFD using LS

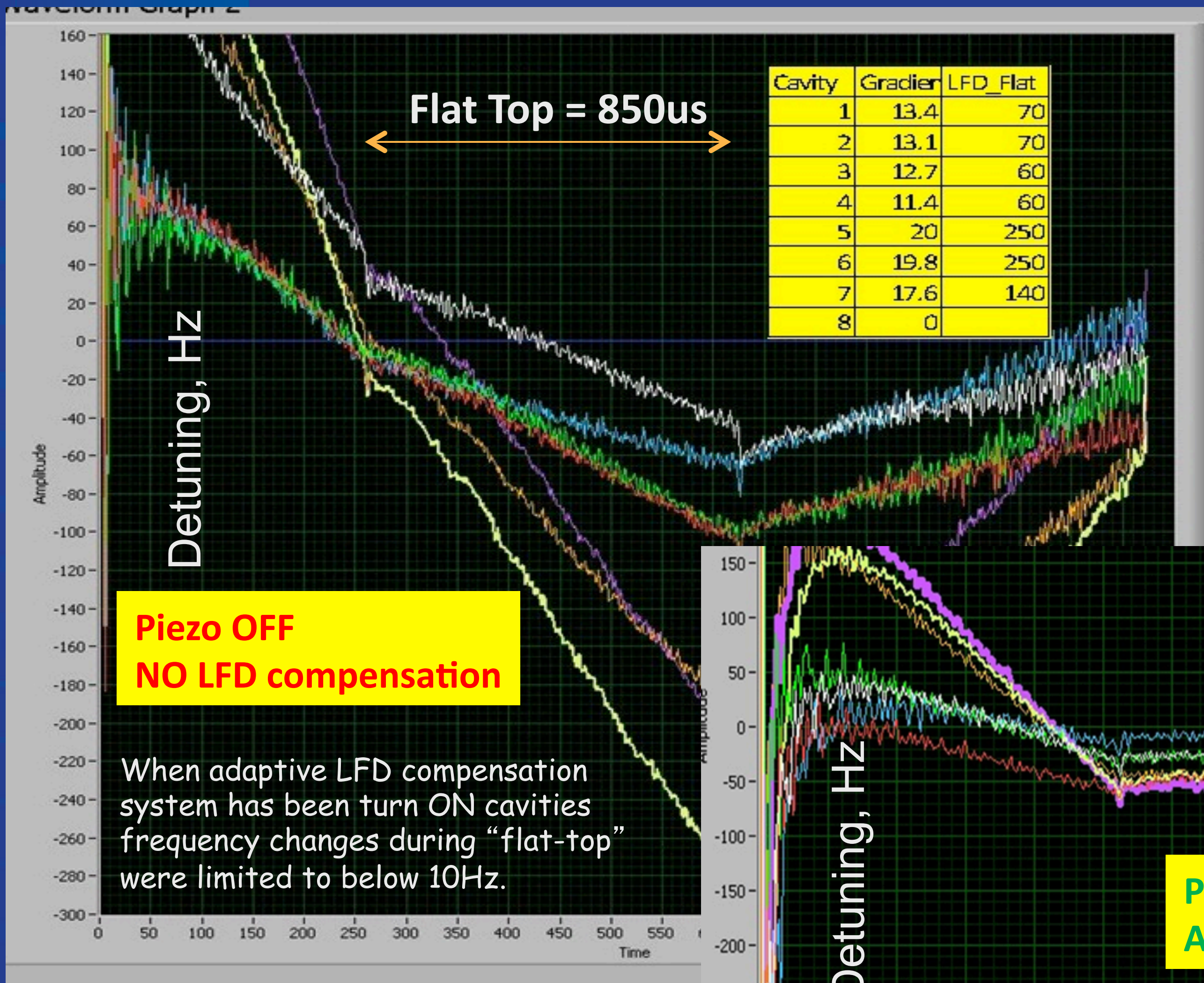
Any part of RF pulse could selected for Compensation:

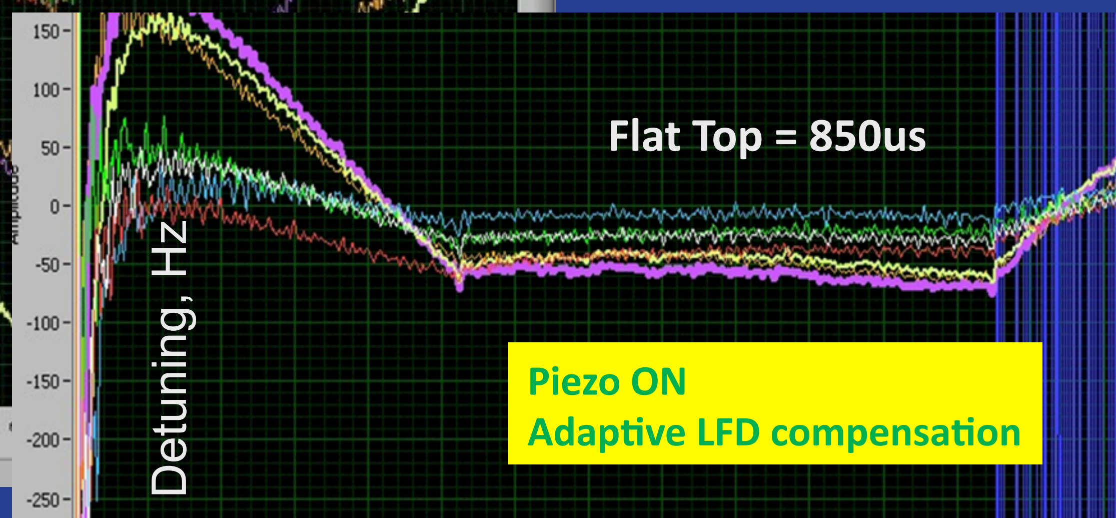
<u>“Fill+FlatTop”</u> only <u>“FlatTop”</u>

Piezo Impulse Calculated by LS LFD algorithm



CM1- 8(7) Cavities LFD Compensation (LLRF in open loop operation)



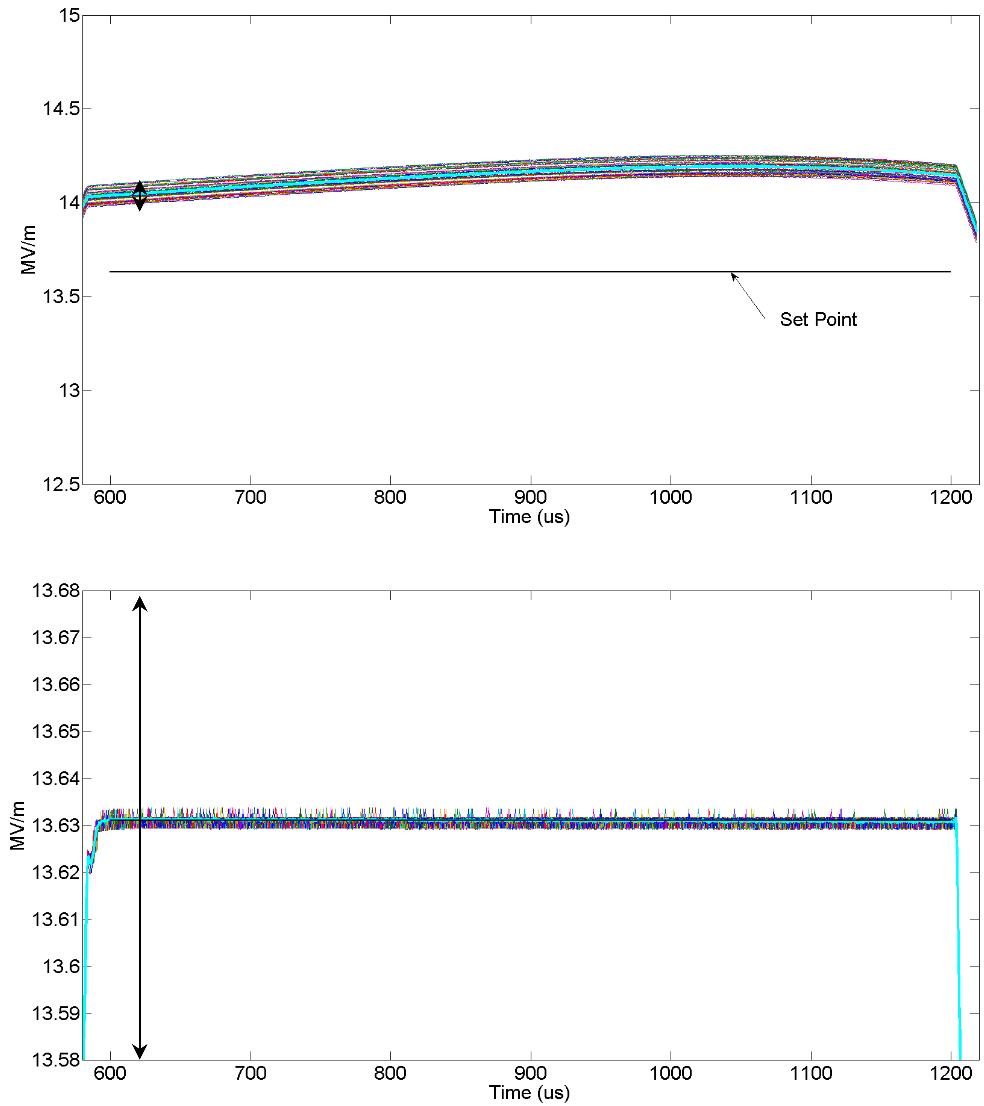


Simultaneous operation of 7 cavities CM1.
Operating gradient range from 11MV/m (#4) up to 20MV/m (#5).
Cavities tune (LFD) during "t=0.85ms flat-top" changed from 60Hz(#4) up to 250Hz (#5).

Low Level RF - Vector Sum Magnitude

Without Feedback

With Feedback



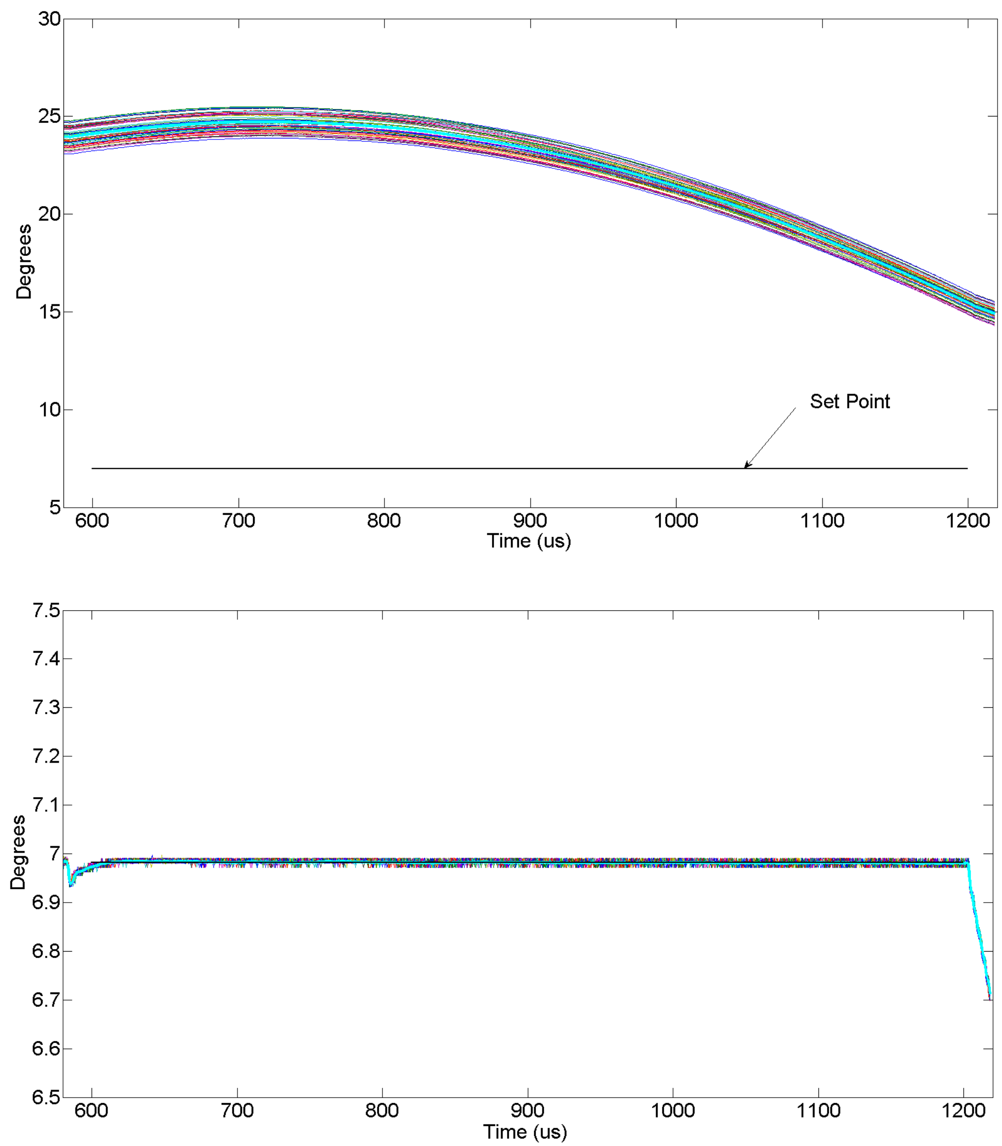
50-pulse overlay in flat-top region

Note: Amplitude Scale Smaller by x25

Low Level RF - Vector Sum Phase

Without Feedback

With Feedback



50-pulse overlay in flat-top region

Note: Phase Scale Smaller by x25

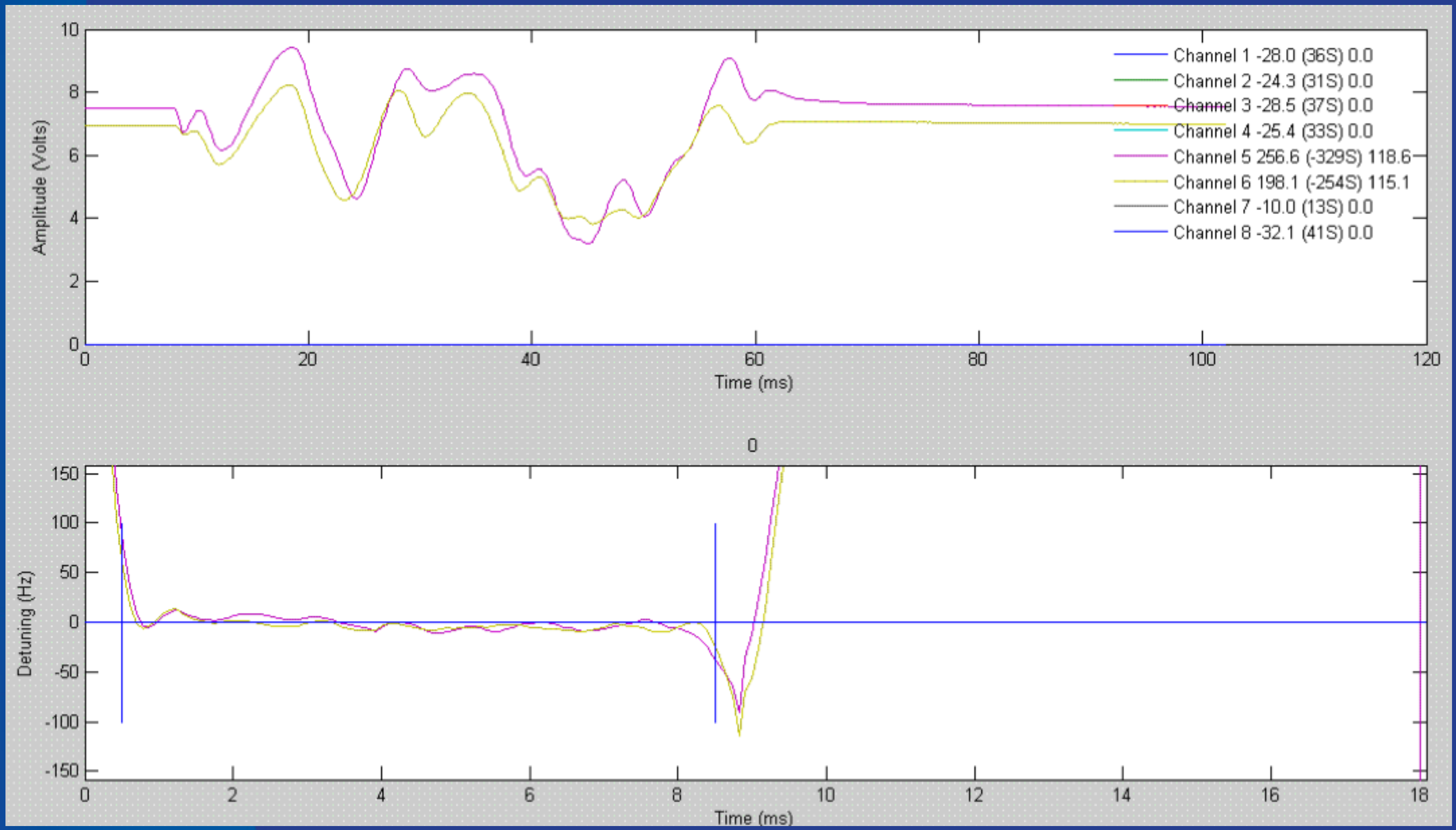
Long Pulse Operation

- Operate the best performing cavity pair under conditions proposed for Project-X cryomodules and determine if preliminary operating parameters are reasonable
- Studies with set of variables in matrix:
  - **RF power limitations: 80 kW**; 100 kW, 120 kW per two cavities.
  - **External Q: 3 X 10^6; 6 X 10^6**; 1 X 10^7
  - **Gradient: 15MV/m; 20 MV/m**; 25 MV/m
  - 9 ms pulse width

- Achieved:
  - Demonstrated overall performance – proof of principle – good first pass test
  - Good LFD compensation at the nominal parameters: Q=1.e7 and 25 MV/m
  - LLRF feedback works; phase stability good to ± 4°
  - Good reliability
- Limitations:
  - Power limitation for low Q case (Q~3.e6). Gradients are limited to < 20 MV/m.
  - System 'very touchy' under dynamic conditions – nearly constant attention required, especially when adjusting power

Long Pulse - 2

- LFD compensation screen with voltages applied to piezo-tuners (cavity #5 and #6) and frequency detuning during 9 ms pulse (below)



Long Pulse – 3

- LLRF screen with zoom of cavity gradient (cavity#5-red, cavity#6-green. Vector sum – yellow, set point – blue) and cavity phase (lower trace).

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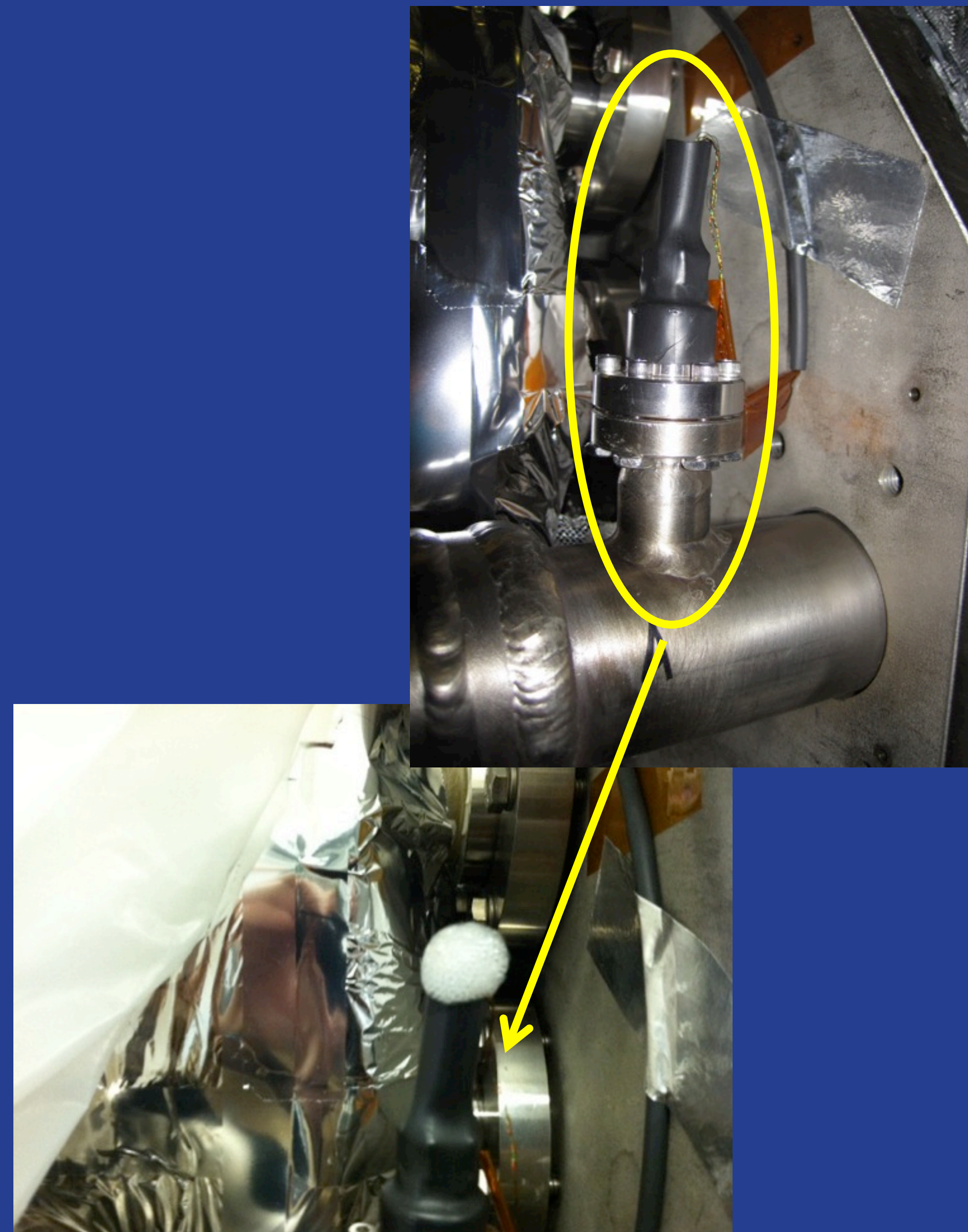
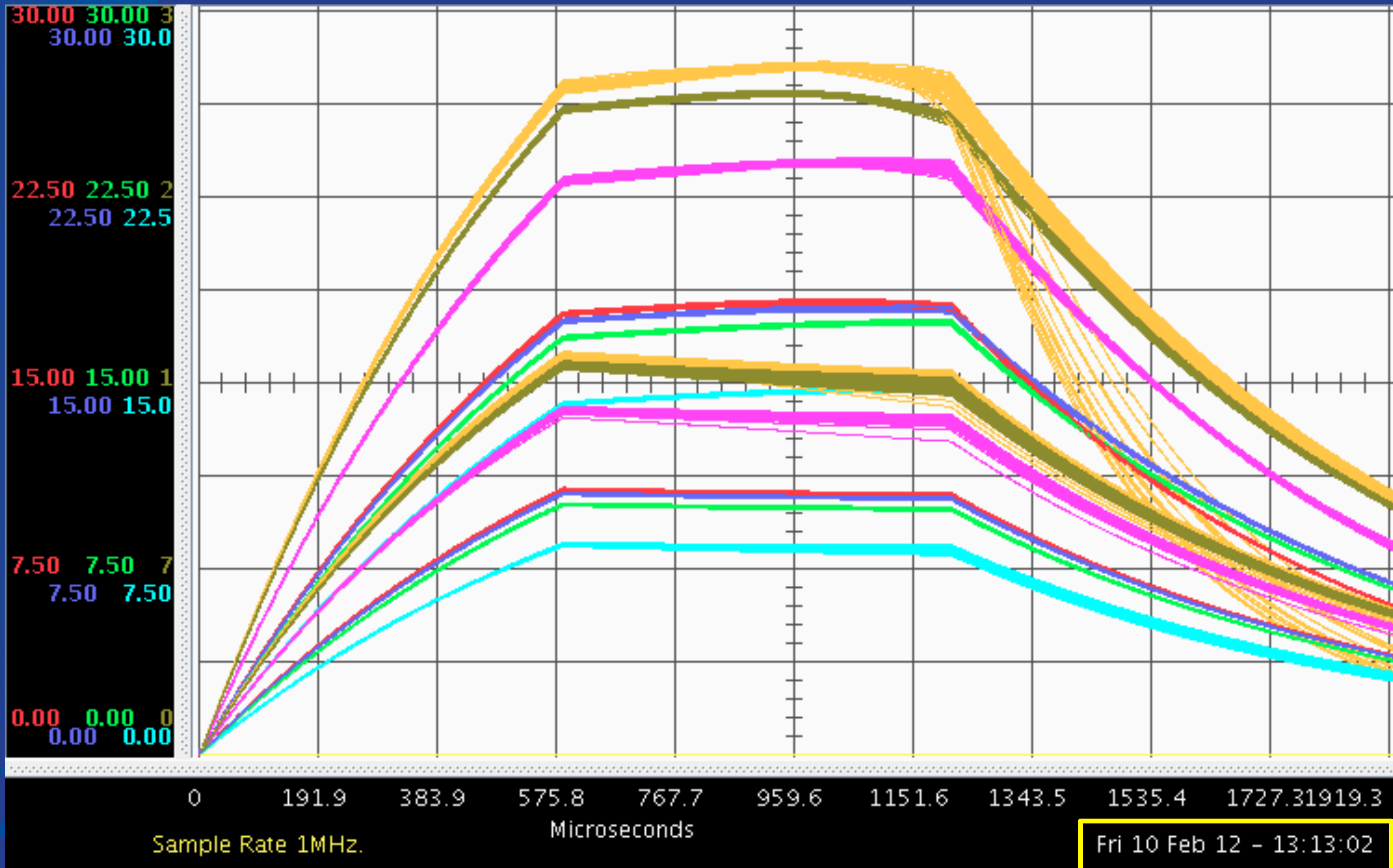
Thermal Cycling

- Warm-up to Room temperature and then cool back down to determine effect on Cryomodule performance, especially lower performing cavities
  - 10 K/hour rate
  - 2-1/2 day – manned 2 shifts/day by cryogenics staff
  - Uneventful warm-up
  - IN_2 leak appeared as cooldown went below 150K
  - Sensors replaced with surface mount ones
  - Valuable experience in identifying and repairing such leaks
  - Subsequent cooldown revealed a helium to insulating vacuum leak – cause for concern, but not a showstopper



Cavity Peak Performance



Remaining Work

- Cease operation at month's end
  - Post thermal cycle performance evaluation (in progress)
  - Dynamic Heal Load measurement of entire module
  - Ongoing LLRF and LFDC studies
  - Localized dosimetry to identify possible source(s) of field emission in Cavity #1
  - Identify location of insulating vacuum leak
  - Strenous testing of fast (piezo) and slow tuners

Not Just Cavity Testing

- Although the priority, CM-1 operation had competition for time:
  - NML as a construction area
    - Tunnel extension
    - Electrical Upgrades
    - Water system
  - Gun window evaluation and conditioning (typically 1-2 days/ week)
  - Photoinjector installation
  - Tours
  - Performance limitations
    - Insufficient LCW capacity and cooling – largely ameliorated since new skid installed and commissioned

Post Mortem

- Once module is warm and open, inspect:
  - Cavity #2 tuner(gets ‘stuck)
  - Cavity #8 tuner (electrical short near motor)
  - Thermal intercepts on Cavities 1, 3, 7, especially HOM cans
  - Piezo on #7 plus possibly others….

Summary

- CM-1 has been in operation since July
- Cavity performance documented
  - Performance degraded by ~82% compared to tests at DESY
  - Limitations not fully understood; some cavities exhibit higher than expected heat loads
- Sub-systems functioning and work well with pretty good reliability
  - HLRF & LLRF
  - LFDC
  - Cryo
- Worldwide knowledge has been expanded esp. LLRF and LFDC
- 'Failures' have been valuable learning experiences
- Fermilab is moving from novice -> expert in Cryomodule operation
- Expanding cadre of capable staff (# of day to day experts tripling)
- This experience has been a valuable test bed for upcoming CM-2 and operation with beam later this year

Thank you for your attention